# Calibrating the Booster Ionization Profile Monitor: Preliminary Summary


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**Abstract**

We have performed a calibration of the Booster Ionization Profile Monitor (IPM) using a new model of the ion dynamics in the detector and independent measurements of the beam width. We obtain the formula

$$\sigma_{measured} = \sigma_{beam} + C_1 N \sigma^{p_1},$$

where $N$ is the current in units of $10^{12}$, $C_1 = (1.13 \pm 0.06) \times 10^{-5} \mathrm{m}^{1-\mathrm{p}_1}/10^{12}$, and $p_1 = 0.615 \pm 0.013$.


## 1 Device Description

The Booster IPM measures beam profiles using ions produced by the beam from the imperfect vacuum of the machine. An applied transverse clearing field causes the ions to drift to a Micro Channel Plate (MCP). The beam direction defines the longitudinal coordinate[1]. The detector is 0.5 m long, with a transverse gap of 12 cm. The MCP plate is $8 \times 10\ \mathrm{cm}^2$and has strip spacing 1.5 mm. The clearing field is 8 kV.

## 2 Theoretical Calculation

We start by considering the scattering of particles in a gaussian beam by the beam itself as well as an applied electric field. The total force felt by an ion in the combined field is

$$\vec{F} = \hat{r}\frac{a}{r}\left(1 - exp(-r^2/2\sigma^2)\right) + b\hat{x}$$

The coefficient $a$ is proportional to $N$, the number of protons in the booster, which we will typically measure in units of $10^{12}$. A typical beam at extraction might have $\sigma = 2.0$ mm and $N = 2.5 \times 10^{12}$. Then

$$\frac{\frac{a}{r_{max}}\left(1 - exp(-r_{max}^2/2\sigma^2)\right)}{b} \simeq \frac{1}{24}.$$

It is possible to analytically calculate the average spread in the $y$ coordinate due to the scattering by the above force to leading order in the small parameter $a$, or, equivalently, the current $N$. The result is

$$< y_{out} >=< y_{in} > +KN\sigma^{-1/2}$$

The constant $K$ is a complicated integral involving the forces and distributions in the problem, but independent of the parameters $\sigma$ and $N$. We assert without proof that the scaling behavior above is insensitive to the detailed shape of the beam distribution. Different beam shapes can only modify the size of $K$. The value of $K$ also depends on the details of IPM such as the distribution of ions, distance to the wall, etc. We will include details and a calculation of the variance of $y$ in a full paper.

| Parameter | Fitted Value | Uncertainty | Units |
|---|---|---|---|
| $C_1$ | $8.44 \times 10^{-6}$ | $0.61 \times 10^{-6}$ | $\mathrm{m}^{1-\mathrm{p}_1}/10^{12}$ |
| $p_1$ | $-0.615$ | $0.013$ | none |
| $C_2$ | $1.8 \times 10^{-14}$ | $1.3 \times 10^{-14}$ | $\mathrm{m}^{1-\mathrm{p}_2}/10^{24}$ |
| $p_2$ | $-3.45$ | $0.12$ | none |

Table 1: Results from power law fit to our simulation.

# 3 Simulations and Phenomenology

We have written a two-dimensional simulation of the physics of the preceding section using Octave. The results of our simulation are consistent with the simulation in Graves's thesis[1]. Since the computer power available to us nine years later than Graves's original work is substantially greater, we have been able to extended our simulations of a larger range of parameter space and to work to higher accuracy. Our new simulation closely matches Graves's simulation in the region of overlap.

Graves used the following formula to parameterize the results of his simulations

$$\sigma_{beam} = \tilde{C}_1 + \tilde{C}_2 \sigma_{measured} + \tilde{C}_3 N.$$

This formula is currently used in the Booster IPM to estimate the true beam width from the measured distribution. The simplest physical observation we can make about the scaling of measured versus real beam widths is that

$$\sigma_{beam} \rightarrow \sigma_{measured} \text{ as N} \rightarrow 0.$$

Unfortunately, the simple parameterization above does not have this property. Inspired by the theoretical result of the previous section, we try the parameterization

$$\sigma_{measured} = \sigma_{beam} + C_1 N \sigma^{p_1},$$

which we refer to as the linear (in $N$) parameterization. Postulating the form of the next term in the expansion, we also consider the quadratic form

$$\sigma_{measured} = \sigma_{beam} + C_1 N \sigma^{p_1} + C_2 N^2 \sigma^{p_2}.$$

In order to test the above parameterizations, we fit a parabola to the quantity $\sigma_{measured} - \sigma_{beam}$ for each fixed $\sigma_{beam}$, then plot the coefficients as a function of $\sigma_{beam}$. The fits themselves are shown in Figure 2. The fitted parameters are shown in Table 1. Returning to Figure 1, we see that the power-law fit with the linear term alone is sufficient for most of the parameter space we explored. It is only in region where $\sigma$ becomes small and $N$ becomes large that the quadratic term in the power-law fit becomes important. Even with the quadratic term, beam sizes around 1 mm are not well described by our fit. Fortunately, beams as small as 1 mm are never observed in the booster under normal operating conditions.

The extracted value $p_1 = -0.615 \pm 0.013$ is similar to, but not exactly the same as, the value $-\frac{1}{2}$ obtained in the calculation of Section 2. In the simulation, we fit the data to a gaussian plus a linear background. (Although the background in the input distribution is zero in the simulation, we include a possible background in the fit in order to best match the fitting procedure used in the actual Booster IPM.) The calculation itself is an estimate of the overall spread in $y$, which is similar to, but not exactly the same as the fitting procedure. The small difference in the powers is therefore not unexpected.

# 4 Measurements

In order to perform an experimental measure of the IPM calibration, we took width measurements simultaneously with the Booster IPM, the MI-8 wire chamber and the so-called "Flying Beam" wire[2]. The "Flying Beam" wire is a single wire measuring device at Long 1, which can be parked just outside the beam envelope of the *injected* beam (i.e

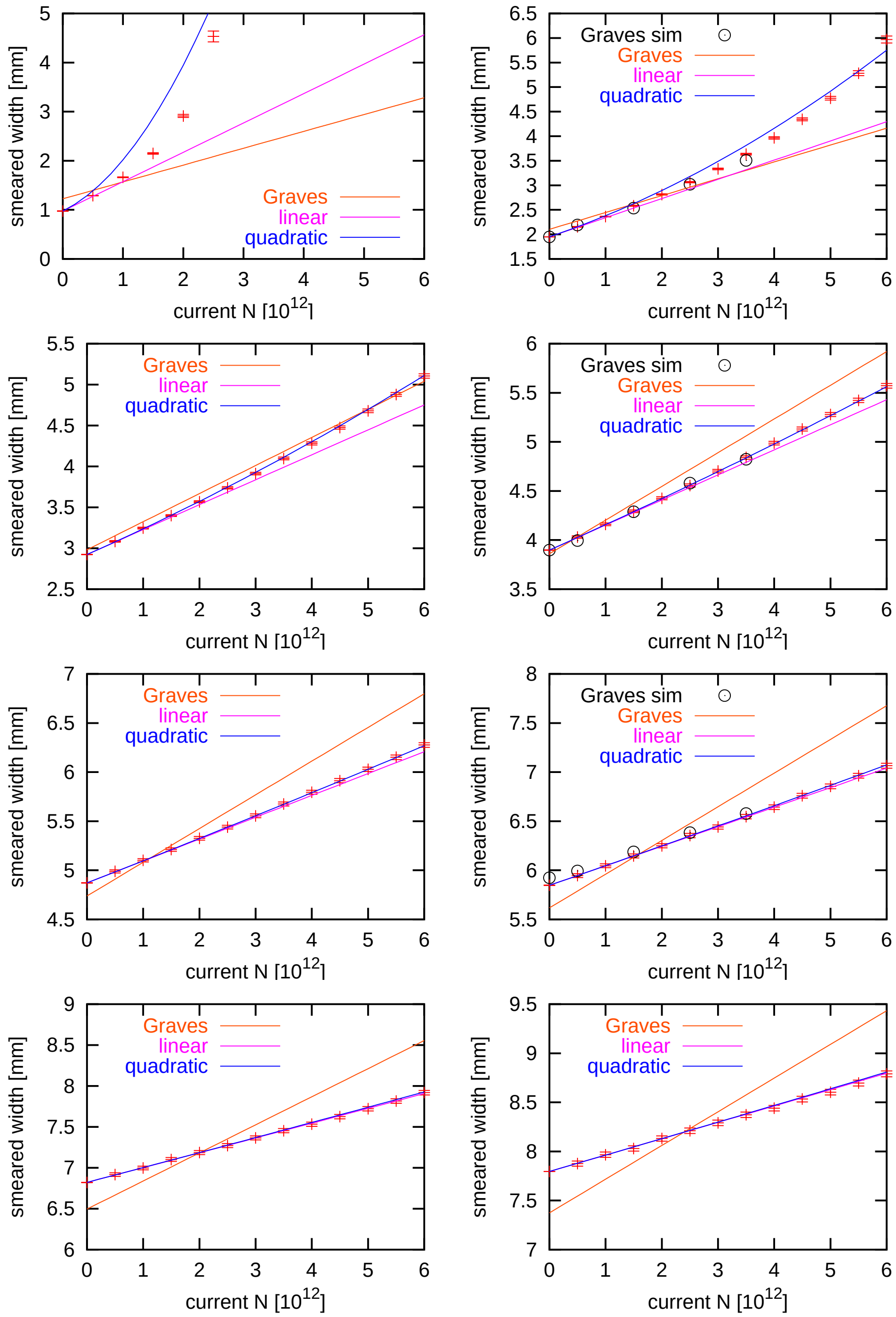


Figure 1: Simulations and parameterizations.

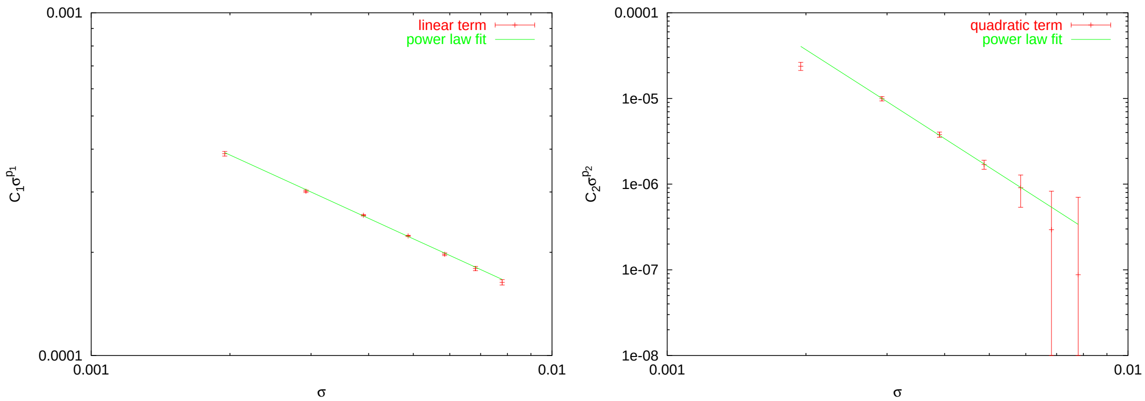


Figure 2: Fits to linear and quadratic terms. The smallest value of $\sigma$was left out of the quadratic term fit to avoid contamination from higher-order terms in the series.

| time | wire width | wire error | IPM width | IPM error | Current [$10^{12}$] | No. IPM points |
|---|---|---|---|---|---|---|
| 1384 | 3.7570 | 0.0072 | 6.406 | 0.118 | 5.030 | 15 |
| 1395 | 3.8778 | 0.0042 | 6.532 | 0.096 | 6.450 | 10 |
| 1371 | 3.2375 | 0.1064 | 4.288 | 0.106 | 0.981 | 43 |
| 1371 | 3.8882 | 0.0017 | 4.393 | 0.024 | 1.258 | 17 |
| 1418 | 3.8305 | 0.0035 | 5.053 | 0.099 | 2.085 | 17 |
| 1418 | 3.7846 | 0.0053 | 5.273 | 0.060 | 3.158 | 11 |
| 1400 | 3.8057 | 0.0015 | 4.868 | 0.046 | 3.295 | 11 |
| 1400 | 3.9399 | 0.0045 | 5.158 | 0.055 | 4.425 | 12 |
| 1380 | 4.0525 | 0.0012 | 5.445 | 0.103 | 3.439 | 7 |
| 1380 | 3.1100 | 0.0928 | 4.552 | 0.291 | 0.550 | 20 |

Table 2: Wire (flying beam) data

beam envelope with the ORBUMP magnets on). As the ORBUMP current decays, the beam sweeps through the wire, providing a measure of the horizontal beam profile. The turn number for which the profile measurement is obtained is controlled by the timing of the injected beam with respect to the ORBUMP current. Therefore our ability to use this technique is linited by the length of the ORBUMP pulse, which amount to roughly 30 turns.

Since the “Flying Beam” wire measures beam widths during the first few turns and the MI-8 chamber measures the beam width after extraction, we were able to see the extremes of the range of beam sizes available. We varied the beam intensity between 1 and 13 injected turns in order to explore a wide variety of intensities. We took data on November 11, 2002 and December 10, 2002.

In order to compare the data from the three different positions in the accelerator complex, each with (potentially) different $\beta$-functions we scaled the widths obtained from the wire and chamber to the IPM by multiplying by $\sqrt{\beta_{IPM}/\beta_{wire}} \approx 0.93$ and $\sqrt{\beta_{IPM}/\beta_{chamber}} \approx 0.82$, respectively. The raw data are summarized in Tables 2 and 3.

In comparing our experimental results with the simulations, we found that all of the data fell in the regime in which the linear and quadratic power-law fits were indistinguishable. As a simple test of the power-law scaling seen in the simulation, we plot the quantity $(\sigma_{measured} - \sigma_{real})/N$ as a function of $\sigma_{real}$ for all of the data and simulation points. We take $\sigma_{real}$ to be the width obtained from the wire or chamber and $\sigma_{measured}$ to be the raw (uncorrected) width obtained from the IPM. The simulation points for a given value of $\sigma_{real}$ will fall on top of each other only to the degree that the linear power-law fit is sufficient to describe the simulation. Because we argued that the constant $C_1$ depends on the details of the beam and IPM, we let it float in order to find the best fit to the data. We did not vary the parameter $p_1$. The value of $C_1$we get from the fit to the data, $(1.13 \pm 0.06) \times 10^{-5}\mathrm{m}^{1-\mathrm{p}_1}/10^{12}$ is approximately one third larger than we obtained from the simulation. Figure 3 shows the scaling behavior of the simulation is quite consistent with the data. Since we have not identified all the sources of systematic errors in the wire measurements we

| chamber width | chamber error | IPM width | IPM error | Current [$10^{12}$] | No. IPM points |
|---|---|---|---|---|---|
| 3.300 | 0.050 | 4.906 | 0.100 | 4.200 | 35 |
| 2.045 | 0.081 | 2.604 | 0.047 | 0.800 | 43 |
| 2.168 | 0.041 | 2.995 | 0.065 | 1.562 | 17 |
| 2.250 | 0.041 | 3.327 | 0.039 | 2.341 | 11 |
| 2.370 | 0.041 | 3.744 | 0.035 | 3.135 | 12 |
| 2.618 | 0.041 | 4.276 | 0.037 | 4.053 | 7 |

Table 3: MI-8 chamber data

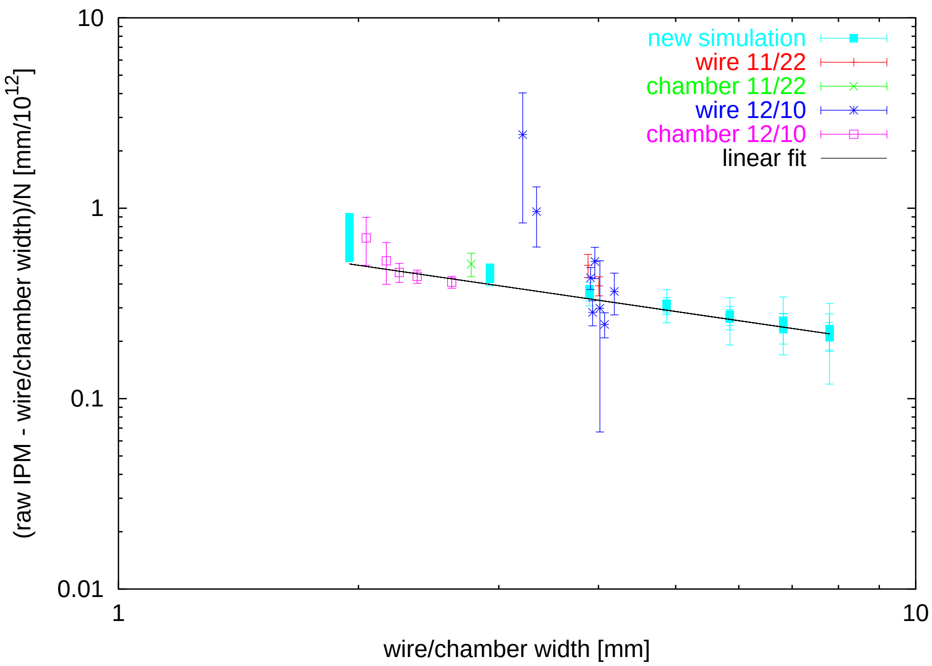


Figure 3: Scaling behavior in the data and simulation. The simulation has been normalized to match the data.

estimate their size from the scatter of the points of Table 2 and Table 3. The result is that the total error is 3 times the statistical error; the total eror is shown in Figure 3.

# 5 Summary

We have found that the relation between the raw beam width seen in the IPM and the true width is well described by the function

$$\sigma_{measured} = \sigma_{beam} + C_1 N \sigma^{p_1},$$

where $N$ is the current in units of $10^{12}$, $C_1 = (1.13 \pm 0.06) \times 10^{-5} \mathrm{m}^{1-\mathrm{p}_1}/10^{12}$, and $p_1 = 0.615 \pm 0.013$. The range of validity in $(\sigma, N)$, can be extended by adding a term quadratic in $N$, but we do not find it necessary to reproduce the data.

# References


[1] Graves, W.S., Ph.D. Thesis, University of Wisconsin, Madison, 1994.

[2] The “Flying Beam” wire was implemented by J. Lackey. Details to be documented in a Booster note.